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ASSESSMENT AND FORECASTING OF LIGHTNING POTENTIAL AND ITS EFFECT ON LAUNCH OPERATIONS AT CAPE CANAVERAL AIR FORCE STATION AND JOHN F. KENNEDY SPACE CENTER

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ABSTRACT

Lightning plays a pivotal role in the operation decision process for space and ballistic launches at Cape Canaveral Air Force Station (CCAFS) and John F. Kennedy Space Center (KSC). Lightning forecasts are the responsibility of Detachment 11, 4th Weather Wing's Cape Canaveral Forecast Facility (CCFF). These forecasts are important to daily ground processing as well as launch countdown decisions. The methodology and equipment used to forecast lightning are discussed. Impact on a recent mission is summarized.

INTRODUCTION

Lightning and its effects can significantly impact safe and timely operations of space and ballistic launch systems from Cape Canaveral, Florida. Determining location, time, and strength of lightning and predicting lightning potential are key support elements provided to CCAFS and KSC by the U.S. Air Force Detachment 11, 4th Weather Wing's Cape Canaveral Forecast Facility. Decision makers and launch operations managers are continually updated on lightning occurrences and forecast probabilities. An extensive network of instrumentation and output displays are available to evaluate these phenomena. New techniques to determine the onset and cessation of lightning are constantly reviewed and applied to both day-to-day operations and launch countdown support. However, implementation of new capabilities is based on safety and operational requirements vice just technical feasibility. During launch countdowns the launch weather team must also evaluate the threat of triggered lightning from high electric field potential aloft. The team requires "clear and convincing evidence" to verify the environment is <u>not</u> dangerous prior to the "go for launch" call by the Range Safety Officer. Continuous instrument and procedure improvements have enhanced the quality of lightning forecasts for these extremely weather sensitive launch operations.

LIGHTNING FORECAST REQUIREMENTS

A major problem confronting forecasters at the CCFF is prediction of the precise time and location of convective activity and its associated weather phenomena, particularly lightning. These storms directly affect a myriad of activities including space and ballistic launch operations and routine

ground processing and gantry operations. Costs associated with lightning induced delays such as cessation of hazardous operations, pad evacuations, and limitation of most outdoor activity are substantial.

Lightning is a year-round concern at Cape Canaveral but the bulk of activity occurs during the months of May through September (see Fig. 1).

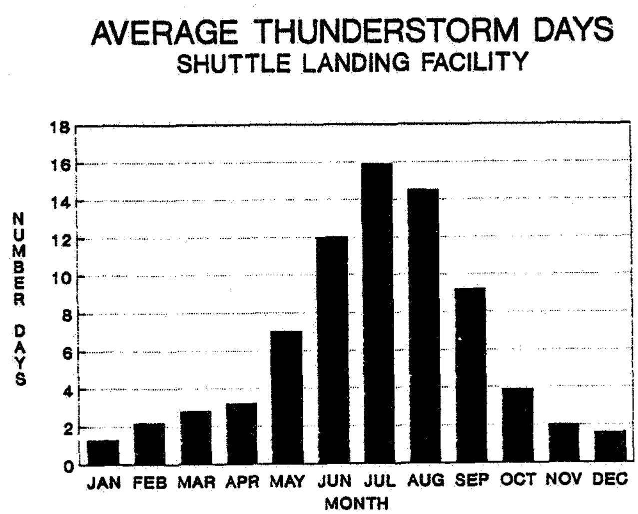

Fig. 1. Average Thunderstorm Days at the Shuttle Landing Facility, Kennedy Space Center, Florida [1].

Lightning assessments are used for planning and real-time operational decisions. Support specifics depend on the type of operation (e.g., daily ground/pad processing or launch) and time requirements. While daily ground operations support requires very precise forecasts of natural lightning for specific places (pads) and periods of time, the decision to launch also includes stringent concerns for triggered lightning.

Lightning forecasts beyond one day are used for planning purposes only. For instance, approximately 5 days in advance of Launch Readiness Reviews (LRR) and daily thereafter, customers are given the probabilities of violating Launch Commit Criteria (LCC) and an overall probability (see Table I). (Table II contains a complete listing of all lightning related LCC.) A critical lightning forecast is given prior to vehicle fueling--launch minus 9 hours for Shuttle and launch minus 5 hours for Expendable Launch Vehicles (ELV). The final launch decision requires the launch weather team to be clearly convinced no weather launch commit criteria are violated.

GROUND PROCESSING SUPPORT

Routine ground processing tasks normally require short-term forecasts. Most commonly, for day to day processing, the forecaster must predict lightning

TABLE I. Launch Constraint Probability Forecast Example

LTG WITHIN 10 NM OF LAUNCH SITE/PLANNED FLT PATH W/IN 30 MIN PRIOR TO LAUNCH UNLESS CONDITIONS CAUSING LTG HAVE MOVED >10 NM AWAY FROM LAUNCH SITE OF PLANNED FLT PATH:	<5%
THRU CU CLOUDS WITH TOPS HIGHER THAN THE +5^{o}C LVL	10%
THRU OR W/IN 5 NM OF CU CLOUDS WITH TOPS HIGHER THAN THE -10^{o}C LVL:	10%
THRU OR W/IN 10 NM OF CU CLOUDS WITH TOPS HIGHER THAN THE -20^{o}C LVL:	10%
THRU OR W/IN 10 NM OF THE NEAREST EDGE OF ANY CB OR TSTM CLOUD INCLUDING ITS ANVIL:	<5%
ONE MINUTE AVERAGE FIELD MILL VALUES EXCEED 1KV/M WITHIN 5 NM DURING THE 15 MINUTES PRIOR TO LAUNCH:	<5%
FLIGHT PATH THRU VERTICALLY CONTINUOUS CLOUD LAYER DEPTH OF 4500 FEET OR MORE WITH ANY PART LOCATED BETWEEN 0^o AND -20^{o}C LEVELS:	20%
FLIGHT PATH THRU ANY CLOUDS THAT EXTEND AT OR ABOVE FREEZING LVL AND ARE ASSOCIATED WITH DISTURBED WEATHER:	10%
THRU TSTM DEBRIS CLOUDS OR WITHIN 5 NM OF TSTM DEBRIS CLOUDS NOT MONITORED BY FIELD MILLS OR PRODUCING RADAR RETURNS:	10%

within 5 nautical miles (nm) of a specific area with lead times of 30 minutes. However, sometimes resources are exposed over long periods of time. For instance, the rollout of the Shuttle from the Vertical Assembly Building (VAB) to the launch complex requires a forecast of a 90 percent probability of no lightning within 20 nm of vehicle rollout path for a period of about 8 hours.

An assessment of lightning advisories issued for the Titan Integrate, Transfer, and Launch (ITL) area, located near Launch Complex 40/41, illustrates the impact to one ELV customer. Figure 2 depicts the time lost due to these advisories in 1989 and 1990. In 1990, the CCFF issued a total of 98 advisories for lightning within 5 nm. Manpower impact is quite large considering the additional time lost exiting from and returning to the pad(s) and platforms. Furthermore, many tests underway were re-initiated from the beginning when prematurely terminated. For instance, Wyatt and Kintigh [2] estimates Titan launch flows are interrupted nearly 380 work force hours per year by lightning advisories. Martin Marietta Corp. (prime Titan Contractor) estimated, on the average, $57,000 per day for manpower costs under normal operations. This translated to an approximate $1 million per year in manpower losses for only one of four major launch systems at the CCAFS. This cost will escalate as Titan launch rates rise. Thus, improving lightning advisories is a top priority.

GROUND PROCESSING LIGHTNING PRODUCT ENHANCEMENTS

Comparisons of 1989 and 1990 advisory data (shown in Fig. 2) suggest recent CCFF enhancements to lightning advisory procedures are reducing downtime. An added manpower position in 1990 allowed the CCFF to dedicate one trained individual to continually evaluate lightning and severe weather potential. Figure 2 also denotes a decrease of more than 10 percent in average lightning advisory duration from 1989 to 1990. A natural consequence of advisory duration reductions is manpower savings. During the non-convective season when not dedicated to day to day support, the individual produces simulations and studies on local effects, and then trains all CCFF forecasters. Initial results are quite favorable.

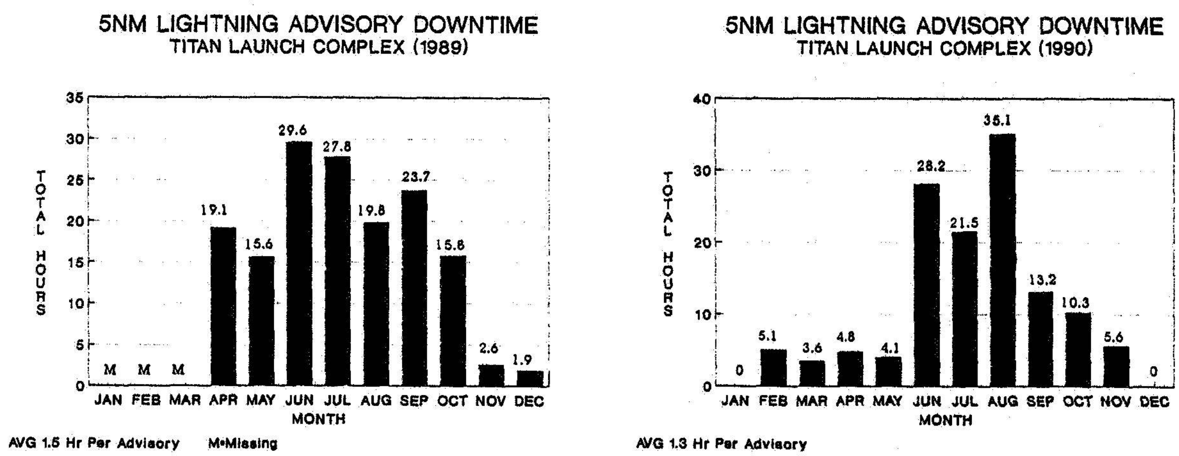

Fig. 2. Lightning Advisory Downtime at Complex 40/41 on Cape Canaveral Air Force Station, Florida in 1989 and 1990.

To reduce the impact of lightning advisories on similar KSC ground operations, a two-tiered (phase 1 & 2) advisory process was tested in summer 1990. The CCFF forecaster issued the initial advisory (phase 1) with a 30 minute lead time when the potential for lightning was expected to move within 5 nm of specified key KSC ground operations areas. This advisory was upgraded to phase 2 when lightning was considered imminent, that is, the threat had actually moved to (or formed) within 5 nm--so called zero minute lead time advisory. Since not all operations required 30 minute lead time, some were allowed to continue until phase 2 was in effect, thus reducing lost man hours. In addition, since phase 2 advisories were not forecasts, they virtually eliminated the false alarms and timing errors of phase 1 advisories. Limited data collected thus far indicates the phase 2 advisories were in effect only 42% of phase 1 advisory time. This two-tiered advisory will continue at KSC and is now being investigated for use on CCAFS in summer 1991.

LIGHTNING ASSESSMENT INSTRUMENTATION

To reduce lost manpower costs and maintain the highest safety standards, the CCAFS and KSC developed a highly sophisticated network of instrumentation. Cape Canaveral Air Force Station/KSC and the surrounding area are host to a myriad of sensing equipment including a lightning detection network, a ground based field mill network, and wind/temperature sensors located on 46 towers at heights ranging from 2 to 165 meters. In addition, a WSR-74C (5 cm wavelength) radar was modified to produce volumetric data sets by McGill University [3]. These data are created at 24 elevation angles ranging from 0.6 degrees to 35.9 degrees over five minute intervals. Data digitization allows forecasters to construct and display constant altitude plan position indicator (CAPPI), vertical cross-sections, and echo tops; animate displays; and extract point information such as maximum tops and radial location. The digitized data is also transmitted to the Meteorological Interactive Data Display System (MIDDS) for processing and display over Closed Circuit Television (CCTV) and merged with other data such as lightning plots or satellite imagery. Location of the radar antenna at Patrick AFB, 21 miles south of Cape Canaveral, reduces ground clutter data loss and produces a full volume scan over CCAFS/KSC.

Equipment falls into four categories: (1) measurement of environmental parameters from which convection initiation can be forecast: Weather Information Network Display System (WINDS)--a network of wind and temperature sensors throughout the CCAFS and KSC complex, see Fig. 3; and the Meteorological Sounding System (MSS)--receives and processes upper air soundings; (2) detection/measurement of lightning associated parameters: Radar (WSR-74C and McGill processor described above); (3) measurement of potential: Ground Based Field Mill (GBFM), also know as the Launch Pad Lightning Warning System (LPLWS)--network of 31 ground based field mills for measuring surface electric potential, see Fig. 4; and (4) detection of actual lightning: Lightning Detection System (LDS), also referred to as Lightning Location/Protection (LLP)--a system of five detectors used to locate and measure cloud-to-ground lightning, and Arthur D Little Lightning Detector --determines occurrence in radial distances, including cloud-to-cloud discharges.

LIGHTNING ASSESSMENT PROCESS

Detection of lightning and/or lightning potential is the focal point of CCFF instrumentation. First the potential for convection is determined from synoptic scale analyses. Next a mesoscale analysis begins with the local upper air sounding released daily at approximately 0615 local time. During the period May through September, a computerized Neumann/Pfeffer [4] climatological regression analysis provides a probability for afternoon/evening thunderstorm occurrence. Examination of satellite imagery and local/regional radar networks identifies mesoscale interactions, e.g., boundary intersections. Meanwhile, the local meteorological sensing networks are monitored to provide important local precursor data for convection initiation (winds, temperature, dewpoint). Techniques developed by the Environmental Research Lab (ERL) in Boulder, CO [4], using total average area divergence are used to identify areas of potential convective

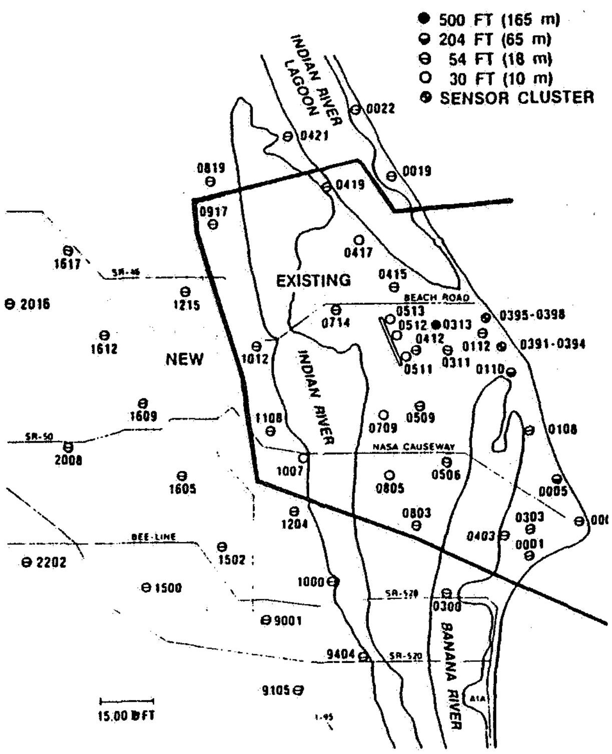

Fig. 3. Weather Information Network and Display System Tower Locations at CCAFS and KSC.

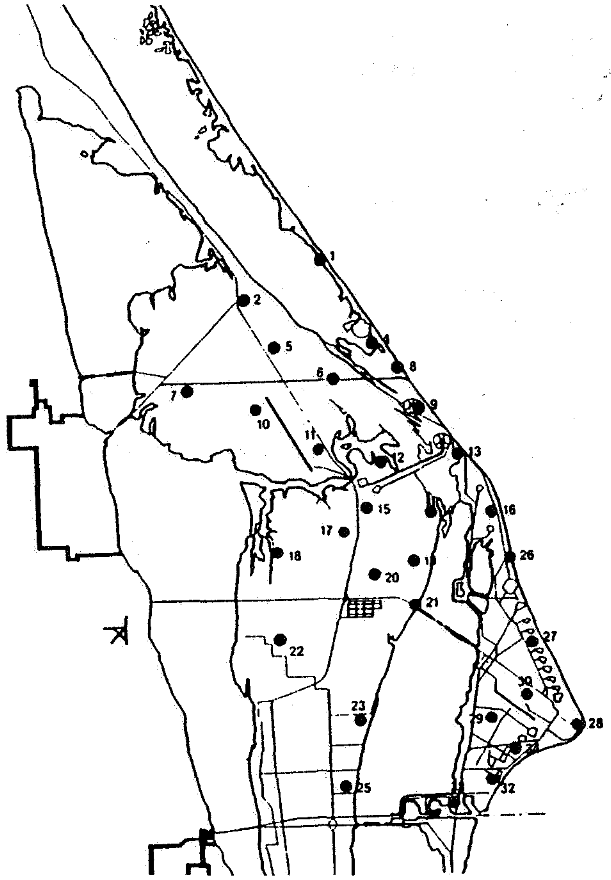

Fig. 4. Ground Based Field Mill (GBFM) Locations at CCAFS and KSC.

growth and hence lightning initiation. When these areas are defined, realtime evaluation intensifies. Radar and satellite are the primary tools to locate developing convection. The GBFM system detects, measures, and contours electric field charge centers and LDS identifies cloud-to-ground lightning occurrence. Integration of all tools is necessary to implement an effective lightning forecast and advisory program.

Forecasting the latter stages of convective decay is also operationally critical. Ground workers are anxious to resume work but typically the threat still exists. This "threat" is not as obvious as when towering clouds, strong winds, rain, and frequent lightning were prevalent. Charge lingers, becomes more concentrated and occasionally initiates powerful lightning discharges.

The debris stage is also critical for launch operations. Space launch vehicles transiting charge-laden clouds from decayed thunderstorms can initiate triggered lightning. On 26 March 1987, an Atlas-Centaur (AC 67) launch vehicle was launched from Pad 36B at CCAFS. At about 48 seconds into its flight, the vehicle was struck by triggered lightning and subsequently destroyed [6]. This incident emphasized the important role weather and weather support play in launching space vehicles. An increased aware-

ness of weather emerged and new lightning constraints were developed. The following constraints (Table II) were formulated by a joint effort of the operational, scientific and academic communities [7].

TABLE II. Range Safety Constraints for Natural and Triggered Lightning

THE LAUNCH WEATHER OFFICER MUST HAVE CLEAR AND CONVINCING EVIDENCE THE FOLLOWING CONSTRAINTS ARE NOT VIOLATED:

A. DO NOT LAUNCH IF ANY TYPE OF LIGHTNING IS DETECTED WITHIN 10 NM OF THE LAUNCH SITE OR PLANNED FLIGHT PATH WITHIN 30 MINUTES PRIOR TO LAUNCH UNLESS THE METEOROLOGICAL CONDITION THAT PRODUCED THE LIGHTNING HAS MOVED MORE THAN 10 NM AWAY FROM THE LAUNCH SITE OR PLANNED FLIGHT PATH.

B. DO NOT LAUNCH IF ANY OF THE PLANNED FLIGHT PATH WILL CARRY THE VEHICLE:

1. THROUGH CUMULUS CLOUDS WITH TOPS THAT EXTEND TO AN ALTITUDE AT OR ABOVE THE PLUS 5 DEGREE CELSIUS LEVEL; OR

2. THROUGH OR WITHIN 5 NM OF CUMULUS CLOUDS WITH TOPS THAT EXTEND TO AN ALTITUDE AT OR ABOVE THE MINUS 10 DEGREE CELSIUS LEVEL; OR

3. THROUGH OR WITHIN 10 NM OF CUMULUS CLOUDS WITH TOPS THAT EXTEND TO AN ALTITUDE AT OR ABOVE THE MINUS 20 DEGREE CELSIUS LEVEL; OR

4. THROUGH OR WITHIN 10 NM OF THE NEAREST EDGE OF ANY CUMULONIMBUS OR THUNDERSTORM CLOUD INCLUDING ITS ASSOCIATED ANVIL.

C. DO NOT LAUNCH IF, FOR RANGES EQUIPPED WITH A SURFACE ELECTRIC FIELD MILL NETWORK, AT ANY TIME DURING THE 15 MINUTES PRIOR TO LAUNCH TIME, THE ONE MINUTE AVERAGE OF ABSOLUTE ELECTRIC FIELD INTENSITY AT THE GROUND EXCEEDS 1 KILOVOLT PER METER WITHIN 5 NM OF THE LAUNCH SITE UNLESS:

1. THERE ARE NO CLOUDS WITHIN 10 NM OF THE LAUNCH SITE; AND,

2. SMOKE OR GROUND FOG IS CLEARLY CAUSING ABNORMAL READINGS.

NOTE: FOR CONFIRMED INSTRUMENTATION FAILURE, CONTINUE COUNTDOWN.

D. DO NOT LAUNCH IF THE PLANNED FLIGHT PATH IS THROUGH A VERTICALLY CONTINUOUS LAYER OF CLOUDS WITH AN OVERALL DEPTH OF 4,500 FEET OR GREATER WHERE ANY PART OF THE CLOUDS ARE LOCATED BETWEEN THE ZERO DEGREE AND THE MINUS 20 DEGREE CELSIUS TEMPERATURE LEVELS.

E. DO NOT LAUNCH IF THE PLANNED FLIGHT PATH IS THROUGH ANY CLOUD TYPES THAT EXTEND TO ALTITUDES AT OR ABOVE THE ZERO DEGREE CELSIUS LEVEL AND THAT ARE ASSOCIATED WITH DISTURBED WEATHER WITHIN 5 NM OF THE FLIGHT PATH.

F. DO NOT LAUNCH THROUGH THUNDERSTORM DEBRIS CLOUDS, OR WITHIN 5 NM OF THUNDERSTORM DEBRIS CLOUDS NOT MONITORED BY A FIELD MILL NETWORK OR PRODUCING RADAR RETURNS GREATER THAN OR EQUAL TO 10DB.

TABLE II (CONTINUED)

G. GOOD SENSE RULE

IF HAZARDOUS CONDITIONS EXIST THAT APPROACH THE LAUNCH CONSTRAINT LIMITS OR IF HAZARDOUS CONDITIONS ARE BELIEVED TO EXIST FOR ANY OTHER REASONS, AN ASSESSMENT OF THE NATURE AND SEVERITY OF THE THREAT SHALL BE MADE AND REPORTED TO THE TEST DIRECTOR OR LAUNCH DIRECTOR.

DEFINITIONS:

1. DEBRIS CLOUD - ANY CLOUD LAYER OTHER THAN A THIN FIBROUS LAYER THAT HAS BECOME DETACHED FROM THE PARENT CUMULONIMBUS WITHIN 3 HOURS BEFORE LAUNCH.

2. DISTURBED WEATHER - ANY METEOROLOGICAL PHENOMENON THAT IS PRODUCING MODERATE OR GREATER PRECIPITATION.

3. CUMULONIMBUS CLOUD - ANY CONVECTIVE CLOUD THAT EXCEEDS THE MINUS 20 DEGREE CELSIUS TEMPERATURE LEVEL.

4. CLOUD LAYER - ANY CLOUD BROKEN, OVERCAST LAYER, OR LAYERS CONNECTED BY CLOUD ELEMENTS; E.G., TURRETS FROM ONE CLOUD TO ANOTHER.

5. PLANNED FLIGHT PATH - THE TRAJECTORY OF THE FLIGHT VEHICLE FROM THE LAUNCH PAD THROUGH ITS FLIGHT PROFILE UNTIL IT REACHED THE ALTITUDE OF 100,000 FEET.

6. ANVIL - STRATIFORM OR FIBROUS CLOUD PRODUCED BY THE UPPER LEVEL OUTFLOW FROM THUNDERSTORMS OR CONVECTIVE CLOUDS. ANVIL DEBRIS DO NOT MEET THE DEFINITION IF IT IS OPTICALLY TRANSPARENT.

TABLE III. Equipment Applied to Launch Commit Criteria

CONSTRAINT	EQUIPMENT/SYSTEMS USED TO EVALUATE CONSTRAINT
A	LDS, GBFM, SURFACE OBS, A D LITTLE
B.1.	RADAR, SATELLITE, MSS, ACFT
B.2.	RADAR, SATELLITE, MSS, ACFT
B.3.	RADAR, SATELLITE, MSS, ACFT
B.4.	RADAR, SATELLITE, MSS, ACFT, SURFACE OBS
C	GBFM (including strip charts)
D	RADAR, SATELLITE, MSS, ACFT
E	RADAR, SATELLITE, MSS, ACFT
F	RADAR, SATELLITE, MSS, ACFT, SURFACE OBS
G	ALL

Table III illustrates the interaction required among instrumentation used to assess launch commit criteria. Common to most constraint assessments are three basic observation processes. First, a process to evaluate conditions necessary to produce/develop mechanisms forming lightning (thunderstorms), i.e., satellite, winds, temperature, etc. Second, a capability to

determine the presence of lightning (LDS, GBFM, A D Little). Finally, a capability to assess the in situ conditions (surface observer, weather aircraft, wind towers).

LAUNCH SYSTEM SUPPORT

The following synopsis illustrates how several tools can be used to evaluate LCC.

Six attempts to launch Eastern Test Range (ETR) Operation #1445 (Delta II) were made 20 May 89 through 10 June 90. Three of the five scrubs were directly related to weather LCC violations with two being especially noteworthy since the equipment and methodology used were unique.

On 23 May thunderstorms were widespread across the northern half of Florida with minor vorticity centers moving across central Florida. These vorticity maximums coupled with a seabreeze convergent boundary produced storms in the local area. The storms were clearly evident in early and mature stages within 10 nm of the launch pad on both satellite and radar but as anvils became detached and moved across the Cape area, volumetric radar data became invaluable. The ability to animate both echo tops and CAPPIs provided clear evidence of anvil origin. The increased resolution of radar data, both spatial and temporal, versus GOES satellite data, left no question of thunderstorm anvil proximity to the launch complex. Dissemination of the data over CCTV enabled the Launch Weather Officer to clearly describe and relay constraint status to decision makers. As the anvil moved over the Cape, field mills became active and exceeded the LCC of 1000 v/m within 5 nm of the launch site.

Two constraints were clearly violated.

A. Do not launch if the planned flight path is through or within 10 nm of the nearest edge of any cumulonimbus or thunderstorm cloud **including its associated anvil.** Determined by radar.

B. Do not launch if at any time during the 15 minutes prior to launch time , the one minute average of absolute electric field intensity exceeds 1 kilovolt per meter **(1 kv/m)** within 5 nm of the launch site. Determined by GBFM.

Launch attempt on 9 June was similar as thunderstorm anvils over the area were detected by satellite imagery and parent cells by radar. An extensive cirrus layer over central Florida masked convection below the canopy. Cells were observable on satellite only in areas where cirrus was not present or tops penetrated the layer. Radar was essential to detect the sources of convection and, in conjunction with satellite data, to determine if the overhead cirrus was thunderstorm associated anvil. Again two separate pieces of equipment were used together to determine constraint status. Analysis showed the parent storms remained outside of 10 nm radius; however, attached debris/anvil were within 10 nm. Thus, as before, the thunderstorm debris LCC was violated and the launch scrubbed.

On 10 June 1990 the satellite and radar data verified no LCC were violated and the Delta was successfully launched.

FUTURE ENHANCEMENTS

Several projects are underway to enhance support. Although not all inclusive, a short summary of new programs is shown below.

AirBorne Field Mill (ABFM) Program . The ABFM program was recommended by the AC 67 investigation committee. Purpose of the ABFM is to gather data to better understand/quantify the meteorological conditions favorable for electric charge aloft and then: (1) evaluate/revise current launch constraints and (2) possibly develop concept of operation to use an ABFM on day of launch. The ultimate goal is to safely increase launch availability and to reduce the chance for weather holds and delays.

A NASA Lear Jet with extensive instrumentation has been flying to 50,000 feet to obtain cloud electrification data in the vicinity of CCAFS. Forty missions were flown in July and August 1990 to calibrate the Lear Jet's five field mills and gather data to revise the LCC. A data analysis report is expected in Spring 1991. Two deployments are scheduled during 1991: February - March and June - July.

Lightning Mapping System. A new Lightning Detection and Ranging (LDAR) System is under development at KSC. The system will map the location of in-cloud and cloud-to-ground lightning based on the time of arrival (TOA) of VHF radiation [8].

Advanced Ground Based Field Mill (AGBFM) System. New more efficient and reliable field mills are being developed as a joint Air Force/NASA project. These mills will replace the current network and have independent processing capability vice the current need for processing on the ETR Cyber Computer.

Applied Meteorology Unit (AMU). The AMU will facilitate the development and transition of new techniques and equipment (such as LDAR) into the co-located CCFF. The AMU will be managed by KSC, manned by contractors, and contain close to a mirror image of CCFF equipment--the AMU will address both the CCFF and the Johnson Space Center's Spaceflight Meteorological Group Shuttle weather requirements.

Improved Weather Dissemination System (IWDS). IWDS is a micro VAX based system designed to simplify and accelerate the transmission of weather forecasts, observations, advisories, and warnings directly to individual user groups. System software is currently under development for CCAFS and KSC. Installation is expected by summer 1991. IWDS will eliminate time consuming dissemination processes and allow for increased forecaster concentration on convective activity.

SUMMARY

Lightning affects time critical launch and ground processing operations at

Cape Canaveral AFS and Kennedy Space Center, Florida. Detachment 11, 4th Weather Wing's Cape Canaveral Forecast Facility produces specific forecasts which allow appropriate personnel to evaluate risks of proceeding with or canceling time sensitive/high cost operational/launch events. Data from an extensive network of sensing equipment is used to evaluate specific launch commit criteria. Methods to reduce lightning impacts without increasing risks are constantly under study. These include both procedural reviews and instrumentation improvements.

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